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Use of Joint Transform Optical Correlators for Precision Image Registration

Robert S. Caprari

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Electronics and Surveillance Research Laboratory

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ABSTRACT

This report contains a survey of the operation and properties of various types of joint transform correlators, as a precursor to their consideration as the central component in analogue optical precision image registration systems. The exact meaning of the term "precision image registration" is articulated. At the very least, an analogue optical system should have the ability to variably magnify and rotate images if it is to have prospects of executing precision image registration. Motivated by this, an appraisal of various optical techniques of image rotation is undertaken. These investigations lead to an objective assessment of the feasibility of conducting precision image registration by suitably enhanced joint transform correlators. Qualitative comparison between analogue optical and digital electronic techniques of precision image registration, favours the latter as the methodology for a practical system.

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EXECUTIVE SUMMARY

Image registration is the process of determining the transformation between two images of the same scene, and then implementing this transformation to yield two images that are views of the same scene from the same perspective, but possibly at different times. This report emphasises the first step of this process, that is, the determination of the transformation. Image registration is essential to a wide range of real time surveillance applications, such as target tracking. Analogue optics is being actively investigated for use in automatic target detection and tracking, its appeal being primarily fast operation from compact hardware. This report considers whether analogue optical techniques can achieve the precision required for high quality image registration, while still maintaining their speed advantages.

Practitioners often adopt a minimalist approach to image registration, whereby the two images are assumed to be translated with respect to one another, but otherwise are identical. The standard mathematical operation of *correlation* in principle will determine exactly the translation vector components. Correlations can be efficiently computed by Fourier techniques, which makes this type of image registration particularly tractable.

However, there are circumstances in which the transformation between the two images is not accurately approximated by a pure translation. Rather, the transformation is parametrised by extra parameters beyond translation; such as rotation, magnification, shear, and nonlinear geometric terms as well. For sufficiently wide field of view imaging systems, the transformation even scales the image intensity in a nonuniform way, thus requiring even more elaborate parametrisation. In such circumstances, image registration becomes a much more formidable problem, and one must take a much more sophisticated approach towards it. For the purposes of this report, the label "precision image registration" will be applied to the problem of registering images with sufficiently high fidelity, that the transformation components additional to translation become important.

Since there are now more transformation parameters to be determined than the two translation components, the computational effort, and hence elapsed time, is increased appreciably. This report examines the radical proposal of attempting to use analogue optical techniques to accomplish precision image registration. The allure of analogue optics resides in the immense speed afforded by its massively parallel operation.

Analogue optical correlation is directly implemented by a variety of *joint transform correlators*. But on its own, a joint transform correlator can only hope to implement the minimalist approach to image registration. This report discusses the embellishments that are needed on a conventional joint transform correlator, to make it a serious proposition as a precision image registration system. Actually, it transpires that even suitably enhanced joint transform correlators make awkward precision image registration systems. On balance, digital computation seems preferable.

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Dr Caprari did his undergraduate study at Adelaide University, obtaining the degrees of Bachelor of Engineering (Honours) and Bachelor of Science, the former majoring in electrical and electronic engineering, and the latter majoring in physics. He then joined OED of DSTO as a PO1, and did research in image processing and imaging system characterisation, before joining EWD as a PO2 and doing research in mathematical and acoustooptic applications to radio frequency signal detection and identification. On obtaining DSTO sponsorship as a Cadet RS, he conducted research in experimental and theoretical condensed matter and electron scattering physics at Flinders University, obtaining the degree of Doctor of Philosophy. Subsequently, he joined LSOD in his current position as an RS, undertaking research into theoretical approaches to image analysis and optical approaches to image processing.

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1 Introduction

Image registration is a substantial and active field of image processing research (refer to Brown [1] for a review). At its most simplistic, image registration involves the determination of the pure translation that best transforms one image into another. This is often quite adequate, especially if one of the images is partioned into small segments, each of which is independently matched to the other image. Image transformation by translation only is the most frequently used type of registration; with subpixel precision claimed for this operation under favourable circumstances (see, for example, Tian and Huhns [2]).

However, in general the transformation between two images of the same scene is not a pure translation, but rather a translation plus other geometric warping components. The exact nature of the image warping due to imaging system rotation has been elucidated by Caprari [3]. Caprari's research demonstrates quite emphatically that there are credible circumstances in which pure translation is a poor approximation to the transformation between images. Under these circumstances, high fidelity image registration necessarily incorporates additional geometrical warping. *For the purposes of this article, the term "precision image registration" will be interpreted as meaning image registration of such high fidelity, that geometric image warping is an essential element of the operation, together with translation.*

Actually, Caprari's research also demonstrates that for wide field of view ($\gtrsim 100°$) imaging systems, there is also a significant radiometric image warping that accompanies the geometric image warping. To simplify matters, this article will consider only registration of image pairs for which the radiometric warping is insignificant; that is, narrow or moderate field of view images.

Precision image registration is such a sophisticated operation, that, to the author's knowledge, it is exclusively implemented as non-real time computations on powerful digital computers. The primary benefit of conducting precision image registration by digital computer, is the ability to implement any conceivable computational algorithm, given sufficient time. For example, in principle there is no reason for a digital computer registration algorithm to exclude the complications of radiometric warping. The primary inadequacy of traditional digital computers is the elapsed time for the registration operation to be completed, by essentially sequential computations. It is true that a reasonably compact parallel computer simultaneously executes several, possibly even many, parallel streams of sequential operations. But even this mode of computation hardly qualifies as being massively parallel, since the preponderance of complexity of the overall operation resides in the sequential procedure.

The purpose of this article is to explore the possibility of executing precision image registration by analogue optical techniques, in lieu of digital techniques. Correlation, which is the basis of all registration operations, can be implemented directly by analogue optical techniques, by a variant of the ubiquitous JTC[1]. The benefit of JTC image registration is its potential for very fast response time, due to the entirely parallel nature of optical correlation. Conventional JTCs only explore pure image translations in their correlation

[1] JTC ≡ Joint Transform Correlator

operation. Herein lies the major problem of JTC registration: its lack of flexibility in exploring more general image transformations. Substantial enhancements to the conventional JTC architecture somewhat broaden the scope of image transformations that are explored by JTCs, but they never attain the supreme flexibility of digital computers. For example, it would be horrendously difficult to include radiometric warping complications in an analogue optical image registration system. Nonetheless, the potential speed, power and size advantages of JTCs over digital computers, makes it worthwhile to conduct an objective assessment of the potential of JTCs to implement precision image registration.

In general, the content of this report consists of an impartial appraisal of JTC and associated optics research that has been published in the scientific literature, from the perspective of precision image registration. It is not the author's ambition to materially advance particular components of this research. Rather, the author's intention is to assess the merits of individual technologies for inclusion in analogue optical precision image registration systems, and to consider the prospective registration performance of conceivable system architectures. In a sense, this report communicates a *gedankenexperiment* in optical system design. The author does not elucidate the physical principles of operation of specific optical technologies. To do so would digress too far from the central theme of this report, and such information is available to varying degrees of detail from the appropriate journal articles that are cited within this report. However, a descriptive account of the operation of conventional JTCs is included, in recognition of the pivotal role of the JTC in any optical image registration system. There is too much uncertainty regarding the performance of individual optical subsystems to enable a definitive quantitative assessment; hence the assessment is qualitative of necessity, but nevertheless is founded upon defensible reasoning.

A concise summary of the operation of JTCs, and the properties and performance of the many variants of JTCs that have been devised, will form the content of Section 2. In Section 2 one will consider only JTCs that are "conventional", in the sense of only implementing the mathematical correlation operation. The meaning and requirements of precision image registration will be reaffirmed and elaborated upon in Section 3. This discussion will convey an appreciation of the enhancements that need to be made to conventional JTCs to improve their suitability for precision image registration. A review of possible techniques for realising these JTC enhancements, and an assessment of their potential for implementation, forms the content of Section 4. In Section 5, conclusions are drawn about the potential of JTCs to be used in precision image registration, and indeed, which types of JTC are the most promising for this application.

2 Properties of joint transform correlators

This section contains a summary review of the properties and performance of JTCs, primarily condensed from the detailed review articles of Javidi [4, 5].

JTCs are coherent optical systems with the generic architecture illustrated in Figure 1, and described in this paragraph. The *reference* and *input* images are juxtaposed

on an *image plane* SLM[2]. This is followed by a Fourier transform lens, with a position sensitive intensity detector located in the back focal plane of the lens. Upon illumination by coherent light, the intensity distribution sensed by the *Fourier plane* detector is impressed upon a Fourier plane SLM, subject to a point transformation of the intensity (ie. the transformation at a point is only a function of the intensity at that point). An appropriate optically addressed SLM, such as a liquid crystal light valve, combines the intensity detection, transformation and spatial light modulation functions into one device. The Fourier plane SLM is followed by a Fourier transform lens, which has an electronically readable position sensitive intensity detector in its back focal plane. Upon illumination of the second stage by coherent light, one obtains a radiation distribution in the *correlation plane* which is peaked at positions representing the translation between similar objects in the two input images. For a linear intensity transformation between the Fourier plane detector and Fourier plane SLM (ie. linear JTC), the intensity distribution in the correlation plane is precisely the square of the correlation function of the images.

Depending on the form of the Fourier plane intensity transformation, one may distinguish between classical linear JTCs, general nonlinear JTCs and binary nonlinear JTCs. Nonlinear JTCs have the following advantages over linear JTCs for image registration: light utilisation efficiency, correlation peak height, sensitivity to image differences and peak to clutter ratios. Binary JTCs exhibit these advantages to the greatest extent of any nonlinear JTC. The sharpness of the correlation peaks, and hence their observability, increases from linear to nonlinear to binary JTCs.

Binary JTCs have the additional practical advantage of being amenable to direct implementation by binary Fourier plane SLMs, as well as continuous amplitude SLMs. Although linear and nonlinear JTCs also may be implemented with binary Fourier plane SLMs (see later for elaboration), there is a complexity penalty for doing so, and they are more suited to the use of continuous amplitude SLMs. Given that the speed of operation of any JTC is limited by the slowest SLM response time, the presence of a continuous amplitude Fourier plane SLM in the JTC will restrict the possible frame rate to below that attainable from two binary SLMs. This contention is premised on the generalisation that in the past, continuous amplitude SLMs have had slower response times than binary SLMs. However, the advent of continuous amplitude ferroelectic liquid crystal SLMs is beginning to remove this disparity.

The Fourier plane intensity transformations used in nonlinear JTCs tend to have the "sigmoid" shape, being linear at low intensity, and saturating at high intensity. Since the spatial frequency spectrum of practical images always is greatest at low frequencies and declines at higher frequencies, a sigmoid spectrum transformation has the effect of emphasising high spatial frequencies relative to low. Accordingly, the influence of image fine structure on the Fourier plane spectrum is enhanced. This explains why the JTC sensitivity to image differences increases with increasing severity of nonlinearity of the Fourier plane intensity transformation.

All of the JTC characteristics described so far indicate that precision image registration is best accomplished by binary JTCs, followed by other nonlinear JTCs in preference to

[2]SLM ≡ Spatial Light Modulator

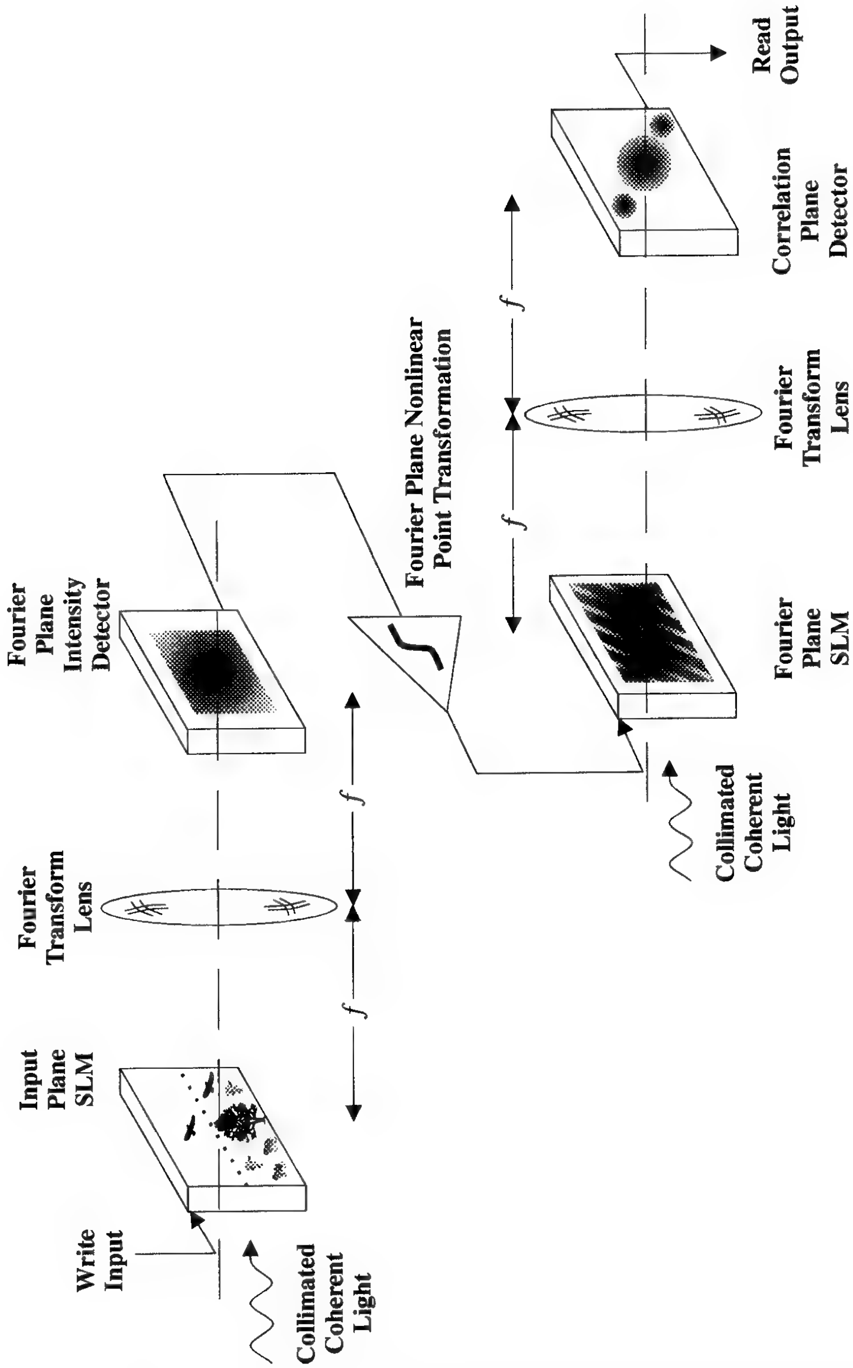

Figure 1: Basic architecture of the nonlinear joint transform correlator (JTC). Electrically addressed spatial light modulators (SLMs) are used. f is the focal length of the Fourier transform lenses. Detectors are position sensitive.

linear JTCs. However, even within the binary JTC constraint, there is still much scope for variation in the JTC specification and design. SLM and detector device types, system architecture and threshold specification are among the remaining undetermined factors.

Javidi [4] contends that the binary JTC gives the best immunity to noise of all three JTC types, when the noise bandwidth is less than the image bandwidth. However, in focal plane array sensed images, the detector noise component of the total image noise is spatially uncorrelated, so the noise bandwidth will be greater than the image bandwidth. Consequently, the correlation peak to clutter ratio is reduced by image noise to a greater extent in the binary JTC than other JTC types. The consequences of this behaviour are ameliorated by the fact that the binary JTC has the highest noise-free peak to clutter ratio. As long as the image noise is sufficiently small, the binary JTC should retain its peak to clutter ratio advantage over the other JTC types. However, the relatively severe degradation of performance of the binary JTC with noise, makes it an unattractive proposition for noisy image registration. It is not clear that other JTC types are any better.

The choice of binary JTC leaves unresolved the specification of the Fourier plane threshold criterion. Three thresholding criteria have been addressed by Javidi [4]. *Optimal* thresholding, which maximises the first order correlation peak, determines the threshold as a function of spatial frequency; in particular, it is the sum of the spectral densities of the input and reference images. Every time an image is changed a new threshold function must be determined by evaluating a Fourier transform. At the expense of increased JTC system complexity, this could be accomplished optically. Alternatively, at the expense of increased total correlation time, it could be accomplished by digital computer. *Median* thresholding is also computationally intensive; without the option of exploiting the existing JTC optical system to apply this criterion, instead of digital computation. *Subset median* thresholding is a reduced computation variation of the median thresholding criterion.

Actually, immense leverage may be gained by judiciously choosing the binary JTC Fourier plane threshold function. By doing so, the binary JTC can emulate an arbitrary linear or nonlinear JTC. Thus, one has a *binary encoded* JTC. This is convenient, since one may wish to utilise a fast binary SLM in the Fourier plane, instead of a slower continuous intensity SLM. The thresholding to achieve this is a function of spatial frequency, depending on the spectral densities of the reference and input images, and on the required nonlinear transformation. This introduces an additional digital computation requirement into the JTC system, which is quite substantial and ongoing, since the threshold function is recomputed every time an image changes. The extra computation time possibly cancels the speed benefits accruing from the use of a fast binary Fourier plane SLM, hence the benefits of this scheme are questionable.

Binary encoded JTCs encounter particularly severe problems in emulating JTCs that are nearly linear. In this case, the higher order correlation terms in the binary encoded JTC are of similar magnitude to the desired first order correlation terms. It is imperative that these higher order correlations be well separated from the first order, thus challenging the SBWPs[3] of both image plane and Fourier plane SLMs, and detector in the latter

[3]SBWP ≡ Space-Bandwidth Product (along one axis of a pixelated image, is just one half the number of pixels along that axis)

case. Although reducing the image resolution relaxes the SBWP requirement for the image plane SLM, no such reprieve is available for the Fourier plane detector and SLM. A conventional nonlinear JTC with a continuous intensity Fourier plane SLM has the advantage of attaining the same correlation fidelity with the use of lower SBWP SLMs.

In the presence of several identical regions in the reference image, linear and nonlinear JTCs are susceptible to confusing and possibly ambiguous correlation plane distributions. This is because the correlation plane contains peaks corresponding to mutual correlation between separate identical regions in the reference image, as well as the desired peaks resulting from cross correlation between the reference and input images. The presence of these diversionary correlation peaks further detracts from the desirability of using linear or nonlinear JTCs for image registration.

Binary JTCs in general are afflicted by the same multiple identical region problems. However, optimally thresholded binary JTCs are devoid of correlation peaks between identical regions of the reference image. The correlation plane of optimally thresholded binary JTCs contains only significant peaks, that is, those resulting from the cross correlation between reference and input images. This characteristic of optimally thresholded binary JTCs makes interpretation of their correlation plane distribution much easier than for any other type of JTC. Another feature of optimally thresholded binary JTCs that further accentuates the "cleanliness" of the correlation plane, is that these JTCs are also devoid of even order correlation peaks. This has the effect of reducing the clutter that interferes with the desired first order cross correlation peaks. These two unique properties of optimally thresholded binary JTCs, suggest that the optimally thresholded binary JTC should be the favoured type for image registration.

Javidi [4] reports the results of experiments conducted on a JTC with a variable Fourier plane nonlinear intensity transformation. These experiments confirm that as the severity of the nonlinearity increases, in the correlation plane one observes an increase in cross correlation peak intensity, an increase in peak to clutter ratio, an increase in peak to sidelobe ratio, and a decrease in correlation peak width. Further experiments on the same JTC demonstrate that the JTC becomes more sensitive to scale and orientation changes between otherwise identical image regions, with increasing severity of Fourier plane nonlinearity. This is detrimental for low fidelity image registration (eg. target recognition), but beneficial for high fidelity image registration. The experimental results demonstrate that the correct scale and orientation produces a maximum in the peak to sidelobe ratio in the correlation plane, relative to other scales and orientations. A problem with observing the peak to sidelobe ratio is that it is a nonlocal quantity, whose neighbourhood is not well delineated, and substantial computational effort needs to be expended in its evaluation. One is again confronted by the necessity to imbue the analogue optical JTC with formidable digital computational power; and even then, it may still be the digital computation requirements that limit the speed of operation of the whole image registration system, especially if both SLMs have fast response times.

The image plane SLM in a JTC must have a high enough SBWP to accommodate one complete image (reference image), and an image segment (input image), the latter possibly also being a complete image. There is also a minimum allowable separation between the reference and input images, to ensure ample separation between autocorrelation and cross

correlation peaks. These are particularly demanding requirements for high resolution imagery. It seems most likely that image resolution would need to be compromised to relax the SBWP requirements to within the capability of present SLM technology. Of course, this would reduce the precision of the image registration performed by the SLM, and there is no scope for compensation by increasing the correlation time.

Assuming that the input image replicates some region in the reference image, the inter-image interference contribution to the Fourier plane distribution takes the form of high spatial frequency fringes modulated by a slowly varying envelope. The spatial frequency of the fringes is proportional to the image plane separation between the two identical image segments. This spatial frequency must be within the Fourier plane detector/SLM modulation transfer function pass band, otherwise the desired cross correlation peak will be suppressed relative to the undesired autocorrelation peak. Therefore, there is a requirement for both the Fourier plane detector and SLM to have high modulation transfer function bandwidths, to ensure full resolution of the interference fringes. This requirement is not diminished by reducing image resolution. It can only be relaxed by reducing the size of the reference image, or its separation from the input image, especially along the direction of the input image.

Nonlinear JTCs have pronounced advantages over linear JTCs in the area of SLM SBWP requirements. The significantly narrower correlation peak width of nonlinear JTCs relative to linear JTCs enables the reference and input images to be located closer to one another in the nonlinear JTC, while still maintaining distinguishability of the cross correlation peaks. This reduces the SBWP requirements of both the image plane SLM and the Fourier plane SLM.

If one requires complete freedom in the specification of the Fourier plane nonlinearity and thresholding criterion, then one must configure the Fourier plane as a distinct position sensitive intensity detector, followed by analogue or digital electronic processing elements to effect the nonlinear transformation including thresholding, followed by an electrically addressed SLM. From a systems perspective, the Fourier plane is composed of three elements, which at present must be implemented with three distinct devices. A single optically addressed SLM as the Fourier plane active element does not have the flexibility to implement an arbitrary nonlinear transformation. This is unfortunate, since from the perspective of system simplicity, an optically addressed SLM would be the favoured option for the Fourier plane.

A variation on the JTC architecture is to display the reference and input images on separate SLMs that are axially separated (thus there are two image planes), obtaining the class of JTCs known as *chirp encoded* JTCs. For reasons to be outlined below, the transmission properties of the two image SLMs must be well matched to give good correlation performance. The requirement for an extra SLM in chirp encoded JTCs is compensated by the need for each image JTC to have only half the SBWP of an equivalent fidelity conventional JTC. Actually, the author has conceived a chirp encoded SLM design with the input and reference images in the same plane (same SLM even), but with a transparent phase retarding plate covering one of the images on the exit side. Varying the thickness of the transparent plate varies the optical path difference between the respective images and Fourier plane, which is the same effect as varying the physical axial separation of the

two images in the absence of the plate.

Chirp encoded linear JTCs have three axially separated correlation planes: one for the autocorrelations, and two for the two duplicate cross correlations. Nonlinear and binary chirp encoded JTCs have their higher order correlation terms focussed on different planes yet again. In chirp encoded JTCs, the correlation plane detector is placed in coincidence with a plane in which one of the cross correlation terms is in focus. All of the other correlation terms (auto and higher order) are out of focus in this plane, and their "peaks" are distributed over an extended area, with a concomitant intensity reduction. Consequently, the other correlation terms do not significantly clutter the desired cross correlation signal.

The transverse separation between the reference and input images no longer has an influence on the performance of the JTC. This separation may be minimised in an effort to minimise the spatial frequency of the Fourier plane interference fringes, and hence minimise the SBWP requirements for the Fourier plane SLM. The use of beam splitters allows the tranverse separation between reference and input images to be reduced to the extent that the two images are optically overlapping. Another benefit of chirp encoded JTCs is that correlations between identical regions in the reference image manifest themselves as peaks in the autocorrelation plane, and not the cross correlation plane.

The requirement for the two image SLMs in a chirp encoded JTC to have well matched light transmission properties is an extrapolation from the theoretical and experimental research of Gregory *et al* [6] on conventional (ie. not chirp or binary encoded) linear JTCs. Gregory *et al* demonstrate that a linear JTC with unequal light transmission through the reference and input image will have only partial interference in the Fourier plane, so that the fringe contrast is lower than that for equal transmission. This is reflected in the correlation plane by a reduction in the intensity of only the cross correlation peaks, but not the unwanted autocorrelation peaks.

Certainly when the autocorrelation and cross correlation peaks are focussed on the same plane, as in non-chirp encoded JTCs, this makes the identification of cross correlations more difficult, because of increased clutter. This introduces a requirement for the two images in the image plane of the JTC to be of similar "brightness", which is not always the case in image registration. Preliminary digital processing may need to be performed to enable the JTC to achieve its full performance potential. This may have an adverse effect on the speed of correlation, and it certainly increases the system complexity. Chirp encoded JTCs would be less sensitive to unbalanced image brightness, since in the cross correlation plane, the autocorrelation peaks are very diffuse, and so the level of clutter is lower. However, even chirp encoded JTCs would suffer a reduction in the signal to clutter ratio in the cross correlation plane, which can't be beneficial.

3 Elaboration on precision image registration

In this section one expands and makes more precise the discussion begun in Section 1, on the characteristics and requirements of precision image registration.

The term "precision image registration" has connotations of the ability to determine the values of many of the parameters that quantify the transformation of one image to another. At the most elementary level is the component of the transformation that represents pure translation. JTCs quantify this parameter by the location of the cross correlation peak. Only one degree of freedom in the JTC output, that is, the correlation peak shape, remains to quantify all of the other image transformation parameters. The obvious way to proceed in the determination of some of the remaining transformation parameters is to "navigate" a low dimensional manifold of parameter space, while seeking the sharpest cross correlation peak. This entails distorting the input image according to the particular location in parameter space.

The design philosophy of JTCs is to maximise the amount of signal manipulation performed by analogue optics, and minimise the amount of digital computation. To conform to this design philosophy, JTCs require controllable analogue optical means to transform the input image. This is an extremely demanding requirement for any transformation that is more complicated than magnification and rotation of the image. Accordingly, one will restrict the JTC to navigating the two dimensional transformation parameter subspace represented by variable image magnification and rotation, with all other image transformations (eg. shear, second and higher order geometric terms, and all radiometric components) tacitly assumed to be zero.

Restricting consideration of image transformation only to translation, rotation and magnification in principle does limit the attainable precision of image registration. This is certainly the case if other transformation components are not negligible; for example, if one image is acquired with shear distortion due to the scanned video line synchronisation steadily drifting from top to bottom, or the shear distortion that would be present in the scanned video image of an object moving rapidly relative to the frame rate. However, in practice one expects that the three transformation components represented by translation, rotation and magnification would frequently account for essentially all of the transformation between the two images being registered. In fact, research by Caprari [3] has demonstrated that even when the transformation between two images has a complicated dependence on position, the transformation of small regions (eg. size being 1/4 of the full image dimensions) is very well described by only translation and rotation; although for large fields of view ($\gtrsim 100°$), components of radiometric warping also become significant. In imaging situations analogous to the one considered by Caprari, image magnification certainly is of lesser importance than rotation or translation, but magnification capability will still be sought, since it doesn't introduce conceptual difficulties beyond those already associated with image rotation.

Thus, there are credible reasons to believe that it is a worthwhile endeavour to seek a precision image registration system that accommodates only translation, rotation and magnification. It is true that a digital computer image registration algorithm could be formulated to navigate a much larger transformation parameter subspace than any JTC, and therefore yield higher fidelity image registration than the less flexible JTC. However, such fine precision would only be available at the expense of immense computational effort, with a correspondingly long registration time.

4 Incorporation of input image rotation and magnification in JTCs

Extensive literature searching by the author has failed to find any concrete examples of JTCs that incorporate either image rotation or magnification, let alone more complicated transformations. However, incorporation of image rotation and magnification in JTCs is not conceptually difficult. In this section one shall consider various image rotation and magnification methods that have been reported in the literature. For image registration, it is the input image segment that is transformed, while the reference image remains invariant.

The following cautionary remark needs to be emphasised for image magnification. Unlike rotation, geometrical magnification also scales the image intensity, by the amount necessary to conserve total image energy. One may encounter the situation of correlating two images of different brightness, which, based on the research of Gregory *et al* [6], was identified in Section 2 as being problematical. Thus, there is a limit to the amount of image magnification that can be tolerated by a JTC before compensatory action must be taken on the intensity. Nevertheless, there is still a large class of image registration applications in which the mutual magnification is quite small.

Jutamulia and Asakura [7] propose a JTC in which a transparency displaying the input image is mechanically rotated, while an SLM displaying the reference image is kept stationary. Their design is just conceptual, with no experimental implementation reported. They are interested in rotation invariant pattern recognition, therefore they superimpose the correlation outputs for all orientations to obtain the single correlation plane light distribution of interest. In contrast, for image registration one must distinguish between correlation plane distributions corresponding to different input image orientations. In the proposed scheme, the input image is displayed on a photographic transparency, so there are no cables to impede rotation. The disadvantage of this arrangement is that producing and inserting new input images is a procession of manual operations, not at all suited to real time implementation. Any registration system with reasonably fast throughput must have the input image displayed on a rotating SLM.

The inertia of the SLM about its rotation axis would be quite high, especially considering that there would need to be a fairly long unsupported span of power and signal cables hanging off of the SLM and rotating with it. This restricts the angular accelerations that would be achieved during SLM reorientations, so that any reorientations take longer to execute. Alignment and positioning of the SLM rotation axis would be of the utmost importance. The continual flexing of cables connected to the SLM as it rotates could lead to fatigue failure of the cables. There would be a maximum angle through which the SLM could be rotated, beyond which the contortion of the cables becomes perilously great. To penetrate this barrier, the SLM would actually have to be rotated through almost a whole revolution in the opposite sense. This is an inefficient procedure, since a very large rotation is undrtaken to achieve a very small effective orientation change. Thus, the design of Jutamulia and Asakura is the most obvious and simplistic method of incorporating image rotation in the JTC, but it may be susceptible to cable deterioration and alignment

degeneration with use. The design is also inherently slow in executing image rotation, because this is accomplished by mechanical means. Its main redeeming feature, apart from conceptual simplicity, is that there is no deterioration of image quality with rotation.

Image rotation and magnification, and indeed a much wider range of geometric transformations, can be effected by the interferometric technique invented by Bryngdahl [8, 9]. This entails multiplying the amplitude image in the front focal plane of a lens by a judiciously chosen phase distribution, so that the required transformed image appears in the back focal plane of the lens. Bryngdahl's scheme essentially is to form the Fraunhofer diffraction pattern of an amplitude object that has been phase modified. It is this phase modification that causes the diffraction to emulate a point transformation.

In Bryngdahl's pioneering research, and that of many following researchers, the phase variation superimposed on the input image is obtained by overlaying either a kinoform or computer generated hologram onto the image. Such phase filters are not amenable to electronic or optical control, requiring the physical removal and insertion of phase plates for variation. They are thus inflexible. The image transformations experimentally achieved by Bryngdahl are very aberrated, and entirely unsuitable for precision image registration purposes.

The interferometric image transformation technique of Bryngdahl is quite elegant, but it only works under some fairly liberal constraints. One-to-one mappings result only if the input image has a sufficiently narrow spatial frequency bandwidth. For images with high spatial frequency structure, the transformed image is expected to be aberrated even more than the already low quality examples given by Bryngdahl. In particular, sharp edges in binary images would be smeared out to some extent in the transformed image; possibly even fringing would occur in the vicinity of the edges. Furthermore, rapid spatial variation of the input image amplitude renders the geometric transformation dependent on the structure of the input image, which is certainly not desired. Any phase variation across the input image area, in addition to the deliberately imposed phase filter, will also reduce the quality of the transformed image even further. It is important to be cognisant of this effect, because some supposedly amplitude modulating SLMs also have an associated phase modulation. In summary, there is plenty of scope for the interferometric image transformation technique to be degraded further than it is in the examples given by Bryngdahl.

The above interferometric image transformation system is based on a Fourier transforming optical system. An alternative interferometric image transformation system suggested by Bryngdahl is based upon an imaging optical system composed of one or more lenses. Such a system needs an extra diffractive or refractive element in addition to the phase filter that realises the image transformation. In effect it causes two transformations. Bryngdahl makes no claims of superiority for this more complicated system.

The Bryngdahl interferometric scheme is complicated by the limited types of image transformations that can be implemented by a single phase filter. For example, neither pure image rotation nor pure image shear are attainable from a single phase filter. Two interferometric transformation optical systems must be cascaded to obtain pure image rotation, with a corresponding doubling of system size, complexity and cost. The first

stage uses a phase filter that performs a combined rotation about the normal to the image plane, and reflection in an axis within the image plane. To cancel the reflection, the second stage must have a phase filter that realises only the same reflection as in the first stage. The need for a two stage interferometric filter patently detracts from the attractiveness of interferometric image rotation, especially considering the low quality experimental results obtained by Bryngdahl for a single stage. Image magnification may be incorporated into the first stage interferometric transformation without the need for further optical componentry; it only requires appropriate modification to the phase filter.

To obtain variable rotation and magnification abilities in the interferometric system, the phase filter must be made variable. A physical mechanism with a proven capacity to achieve this property is the electrooptic effect, in which the refractive index distribution across a film of suitable material responds to the nonuniform macroscopic electric field within the material. A very suitable material for exploiting the electrooptic effect is a liquid crystal film. The electric field nonuniformity is achieved by varying the voltage across pixelated, transparent electrodes that have been deposited on the two faces of the film. One has just described liquid crystal phase SLMs, which are a well established, but still progressing, electrooptical technology. It follows that liquid crystal phase SLMs have prospects for use as electronically configurable phase filters.

The SBWP limitations of the SLM phase filter will become apparent if the required phase filter fringe pattern is too fine, which it probably would be if one were to insist on high fidelity image transformation. For each different image transformation, the necessary phase filter fringe pattern must be recomputed and rewritten by resetting the electrode voltages on all pixels; a task that requires significant computational resources and elapsed time. Perhaps the most seductive property of interferometric image transformation by the use of an SLM phase filter, is that it furnishes true electronic image transformation, with absolutely no moving parts. Thus, potentially it is a very rugged, reliable, and energy efficient scheme. Also, the absence of macroscopic mechanical relaxation times following any adjustment, offers the opportunity for relatively fast operation; limited only by liquid crystal SLM relaxation and digital computation times. The only other variable image transformation technique whose implementation is completely rigid mechanically, is the $\ln r$-θ to cartesian image transformation discussed below, which has its own severe SBWP capacity problems.

Braunecker *et al* [10] consider the use of crossed one dimensional Fresnel zone plates as diffractive elements superimposed on the image in the front focal plane of a lens. The back focal plane of the lens contains the rotated and magnified image, the amount of rotation and magnification depending on the orientations of the two Fresnel zone plates. Two off-axis portions of Fresnel zone plates are utilised in this diffractive scheme, in contrast to the use of a single hologram in the original Bryngdahl [9] interferometric scheme. In the two Fresnel zone plates scheme, image rotation and magnification are achieved by rotating the invariant zone plates, whereas the original holographic scheme achieved the same effect by varying the fringe pattern. The Fresnel zone plates scheme performs rotation and magnification in one optical stage, as opposed to the two optical stages required for the single hologram scheme. In common with the single hologram technique, the two Fresnel zone plates technique restricts the spatial frequency bandwidth of the image for good

results to be obtainable. Experimental results presented by Braunecker *et al* indicate a severe degradation of image quality resulting from this diffractive method of image transformation; quite reminiscent of the earlier interferometric method of Bryngdahl.

Braunecker *et al* [10] also present a refractive analogue of their diffractive system, in which the Fresnel zone plates are replaced by adjacent convex and concave cylindrical lenses of equal focal length (same magnitude, but opposite sign). The lenses are centred on the optical axis in this refractive architecture, in distinction to the use of off-axis portions of Fresnel zone plates in the diffractive architecture. Once again, independent rotation of the two lenses about their optical axis yields both rotation and magnification. Subject to the absence of lens aberrations, the refractive system has the important advantage over the diffractive and interferometric systems, that it rotates and magnifies images without degradation, no matter how wide the spatial frequency bandwidth of the images. Certainly, the experimental results presented by Braunecker *et al* for the refractive technique are much better than those for its diffractive counterpart, and indeed, the original interferometric technique. Braunecker *et al* concede that their refractive scheme definitely is superior to their diffractive scheme.

It transpires that the cylindrical lens image rotation and magnification scheme adopted by Braunecker *et al* is ubiquitous, having been included in the earlier review of Swift [11]. Swift's cylindrical lens image rotator consists of three cylindrical lenses, whereas Braunecker *et al* [10], in both their text and figures, imply that the same effect may be achieved with just two cylindrical lenses. However, the author does not accept Braunecker *et al*'s contention that two cylindrical lenses alone are sufficient to rotate the image. The important parameter for image rotation action, as asserted by Braunecker *et al*, is the orientation of the bisector of the cylindrical axes of the two cylindrical lenses (the cylindrical axes are perpendicular to the conventional optical axis of the lens system, which is in turn normal to the image plane, and along which all optical elements are aligned). But if all other optical elements in the system are rotationally symmetric about the optical axis, or if there are no other optical elements, the orientation of the bisector can not influence the image rotation produced by the optical system. Reflection symmetry arguments preclude the possibility of image rotation, although the same symmetry considerations do not account for the absence of image distortion as well. Following the scheme of Swift, the inclusion of a third cylindrical lens breaks the previous reflection symmetry, if its cylindrical axis is neither parallel nor perpendicular to the aforementioned bisector. There is now an identifiable datum from which the bisector direction is uniquely specified, and it is conceivable that rotating the bisector direction (i.e. rotating the original pair of cylindrical lenses together) will also rotate the image. Since Braunecker *et al* present experimental results that quite clearly demonstrate image rotation, one can only conclude that their actual optical architecture included at least one non-rotationally symmetric optical element that was omitted from their discussion and diagrams.

Notwithstanding the incompleteness of the description presented by Braunecker *et al*, their refractive image rotation and magnification scheme demands attention. It has demonstrably, although not unequivocal, good performance, and is not too complex for incorporation in practical JTCs. It is worthy of consideration for any application that requires combined rotation and magnification of images, with good retention of image quality. On

the basis of available information, and from the perspective of present electrooptical technology, this double cylindrical lens image rotation and magnification technique seems to be the best of all the methods considered in this report.

It is common knowledge among researchers that the $\ln r$-θ [4] to cartesian coordinates image transformation, converts mutually rotated and magnified image pairs into pairs of identical warped images that are translated with respect to one another. The translation component along the $\ln r$ axis yields the magnification, and the translation component along the θ axis yields the rotation. Conventional correlation techniques, such as a JTC, in principle are then able to determine the translation components. Casasent and Psaltis [12] are among the proponents of this technique for rotation and scale invariant pattern recognition. The same technique should be equally successful for registration of mutually rotated and magnified images as it is for pattern recognition. The $\ln r$-θ to cartesian transformation is very appealing, because it dispenses with the need to explicitly rotate and magnify the input image in a quest for the optimum rotation and magnification, hence it endows conventional correlators (such as JTCs) with the ability to determine rotations and magnifications. However, there are severe problems with this technique.

One may demonstrate that the $\ln r$ to x transformation increases the one dimensional SBWP along that axis alone by a factor of $\ln N/\sqrt{2}$ [5]; and that the θ to y transformation increases the one dimensional SBWP along its axis by a factor of $\sqrt{2}\pi$ (for an indication of a method of derivation, refer to Casasent and Psaltis [13]). Consequently, the $\ln r$-θ to cartesian transformation increases the two dimensional SBWP of the image by a factor of $\pi \ln N \approx 17.4$ for a modest image size of N=256, and $\pi \ln N \approx 8.7$ for a modest image segment size of N=16. JTCs are inherently demanding on SLM SBWP, since both the reference image and input image usually are displayed on the same SLM; and in the case of precision image registration, the large, high resolution reference image is particularly demanding of SBWP capacity. Hence, there seems to be very little scope for current or prospective SLM technology to tolerate demands for up to eighteenfold increases in SBWP capacity. To implement the $\ln r$-θ to cartesian transformation on present SLMs would necessitate a severe diminution of image resolution, which is contrary to the notion of "precision" image registration.

A more fundamental problem with the $\ln r$-θ to cartesian transformation is that it has the simple interpretation articulated above, only when the two images have corresponding image points at the origin of their respective coordinate systems; essentially, there is no translational misregistration. However, one does not have prior knowledge about corresponding pairs of points in the two images that are suitable coordinate system origins. The favoured scheme for overcoming this problem, is to register the Fourier transform magnitudes of the images, rather than the images themselves. Using the Fourier magnitude distributions removes all uncertainty about appropriate coordinate system centres—one uses the origins of the Fourier spaces of the two images. Unfortunately, by discarding the Fourier phase information, one forfeits any possibility of extracting the relative image translation vector concurrently with the magnification and rotation. Casasent and Psaltis [12] report experimental results of a matched filter type correlator implementa-

[4] r and θ are plane polar coordinates

[5] for an $N \times N$ pixel untransformed image

tion of the $\ln r$-θ to cartesian transformation. Tentatively, their results seem to be of satisfactory quality, but they are possibly assisted by the simplicity of the test images.

A feasible solution to this problem could be to determine the optimal magnification and rotation first, by the $\ln r$-θ to cartesian transformation applied to the Fourier magnitudes, as described above. Then one could magnify and rotate the input image accordingly, and determine the translation by a second, conventional correlation. Thus, two correlations would need to be performed for every image registration; one to determine the magnification and rotation, and the other to determine the two translation vector components. This would double the time required to undertake the registration. Nevertheless, this technique does have appeal, because it is completely devoid of mechanical motion in the JTC, and also because it is the only technique discussed here that determines all image transformation parameters without recourse to an iterative search. Its most debilitative problem is its extremely high SBWP requirement. Casasent and Psaltis [12] propose an alternative, sophisticated, but complicated, method of simultaneously determining image translation, rotation and magnification. It is not at all obvious that their proposal has merit as a contender for a practical system.

The standard method of optically rotating an image is by the use of a Dove prism, or one of its analogues, as discussed by Swift [11] and Ginsberg [14]. In the context of JTCs, the Dove prism would be inserted longitudinally along the optical axis of an imaging system that precedes the conventional JTC input image SLM. The input image to be registered now would be displayed on a screen in the front focal plane of the imaging system. It is not necessary for the light emanating from the input image to be coherent, so that any display screen would be suitable, not just coherent display devices such as SLMs. The rotated image would be projected on a position sensitive detector in the back focal plane of the imaging system. Finally, the detector light distribution is impressed upon the JTC input image SLM, to be correlated with the image on the JTC reference image SLM. The position sensitive detector and JTC input image SLM may be implemented as a single optically addressed SLM, instead of two distinct devices.

Rotation of the Dove prism around the optical axis by a certain angle, causes the projected image to rotate by twice that angle. An adjustable zoom lens arrangement may be incorporated into the same imaging system that includes the Dove prism. The resulting JTC would have mechanically variable rotation and magnification of the input image. Quality of the transformed image should be dependent on primarily the optical quality of the Dove prism and zoom lens. Dove prisms introduce coma and astigmatism aberrations (Bushmelev *et al* [15]), which can be partially corrected by appropriate imaging lens modifications. Although the quality of the transformed image is only slightly dependent on the alignment of the Dove prism and zoom lens, the position of the transformed image in the input image plane of the JTC depends sensitively on this alignment. It follows that the position of the correlation peak, but not its magnitude, also depends sensitively on this alignment, which is a detrimental feature of this technique.

Any practical implementation of such a JTC would need careful attention devoted to achieving mechanical precision and ruggedisation. This is a challenging undertaking given the mechanical complexity of this scheme. However, the Dove prism and zoom lens technique for image rotation and magnification warrants attention, because none of its

problems are insurmountable by the best technology presently available. Judged from a practical perspective, probably this would be the second most favoured image rotation and magnification method, after the double cylindrical lens method of Braunecker *et al.*

5 Conclusion

To the author's knowledge, a successful JTC based precision image registration system has never been implemented, or at least reported in the literature. Upon reading this report, which addresses only the more obvious and fundamental problems, this should not be surprising. Basically, conventional JTCs are incapable of implementing even the most rudimentary image warping required for precision image registration. And suitably enhanced JTCs tend to be mechanically complicated, while requiring substantive embedded digital computational power, thus defeating the purpose of analogue optical image registration.

Specific problematical aspects of the optical architectures identified in Sections 2 and 4 include: the high rotational inertia of the refractive optical elements that are rotated, whether they be cylindrical lenses or a Dove prism; in the case of a rotating Dove prism, the axis of rotation is not one of its dynamical principal axes; the susceptibility of the drive mechanisms for the mechanical degrees of freedom to backlash; the complicated nature of the correlation plane light distribution for some JTC architectures, with its attendant requirement for heavy computation to extricate the desired cross correlation peaks; the possible need to compute nonlinear JTC Fourier plane threshold functions; the need to instigate a sophisticated, two dimensional rotation and magnification parameter space optimisation strategy, which involves much computation; the centrality of optical to analogue electronic to digital conversion processes, and vice-versa, with their attendant response times; and the relatively long relaxation times of the mechanical transient responses.

If one were to attempt the design and construction of a JTC based precision image registration system, then this report would assist one in forming a distinct preference for particular system architectures over all other alternatives. Based upon the survey of conventional JTCs that is undertaken in Section 2, it seems that the most promising JTC architecture is the chirp encoded binary variety; with a Fourier plane threshold function that is preferably invariant, or at worst, simple to compute (i.e. definitely *not* optimal thresholding). Additionally, one would configure the reference and input images to be optically overlapping, which is a trivial matter if a beam splitter is included (which it probably would be, regardless of this requirement). As explained in Section 3, in deference to the difficulty of optically warping images, one enhances the conventional JTC only by including image magnification and rotation capabilities. Based upon the survey of optical image rotation techniques that is undertaken in Section 4, it seems that the most promising technique for optically rotating and magnifying images is the double rotating cylindrical lens scheme of Braunecker *et al* [10]. The next best optical image rotation and magnification technique seems to be the "obvious" one of a Dove prism and zoom lens combination.

Any such optical precision image registration system would have two characteristics that substantively nullify the presumed advantages of JTCs. The mechanical adjustability of the system makes it bulkier, more complicated, slower, less rugged, less energy efficient and less reliable than an unadorned JTC. Compounding some of these problems, is the inclusion of considerable electronic control and computer hardware, that would not be present in unadorned JTCs. Given that the principal reason for seeking an analogue optical approach to precision image registration was to avoid the use of a digital computer for anything other than simple operations, one would conclude that this quest has failed. The JTC design that shows the most promise, has an embedded digital computer as an indispensable element; and if that doesn't impede the rate of registrations too much, then the mechanical adjustments certainly will!

An objective appraisal of the capabilities of optical correlators in the context of the requirements of precision image registration, affords one little enthusiasm for using the former to accomplish the latter. Digital computers are much more adaptable towards the sophisticated operations required for precision image registration. Since the precision image registration problem is expressed mathematically (with no scope for singularities or diverging integrals or series), there is a computational algorithm that solves the problem to arbitrary precision, and one may conceive of a digital computer that can execute this algorithm. The only remaining issue is the time taken for the solution of the problem. Even if practicable digital computers are too slow for the application that is envisaged, given the above revelations, there is not much reason to believe that practicable optical precision image registration systems are any faster. Analogue optical systems certainly would not be more precise than digital computers.

Based upon the current state of analogue optical versus digital electronic technology, it is the author's considered opinion that it would be more fruitful to appeal to the latter technology in tackling the problem of precision image registration.

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19. Abstract
This report contains a survey of the operation and properties of various types of joint transform correlators, as a precursor to their consideration as the central component in analogue optical precision image registration systems. The exact meaning of the term "precision image registration" is articulated. At the very least, an analogue optical system should have the ability to variably magnify and rotate images if it is to have prospects of executing precision image registration. Motivated by this, an appraisal of various optical techniques of image rotation is undertaken. These investigations lead to an objective assessment of the feasibility of conducting precision image registration by suitably enhanced joint transform correlators. Qualitative comparison between analogue optical and digital electronic techniques of precision image registration, favours the latter as the methodology for a practical system.